NOAA Technical Report NESDIS 134

Report from the Workshop on Continuity of Earth Radiation Budget (CERB) Observations: Post-CERES Requirements

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Report from the Workshop on Continuity of Earth Radiation Budget (CERB) Observations: Post-CERES Requirements

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EXECUTIVE SUMMARY

The exchange of radiative energy between the Sun, Earth and space affects the genesis and evolution of Earth's climate. The Earth's radiation budget (ERB) is determined by two components: solar radiation that the Earth absorbs from the Sun and thermal radiation that the Earth emits to space. Uneven distributions of these two components in the Earth system and their regional patterns drive the atmospheric and oceanic circulations as well as associated hydrological and energy cycles. In an equilibrium climate state, the global net radiation (difference between solar radiation absorbed by Earth and thermal infrared radiation emitted back to space) at the top of atmosphere (TOA) is zero. The Earth's climate system tends to restore the equilibrium from any TOA radiation imbalance by changing the energy flows in the climate system and adjusting to a new temperature. However, because of the mismatching response time scales of the atmosphere, land, and ocean, the climate is not in static equilibrium — there is a constantly varying small imbalance of the TOA net radiation.

Anthropogenic climate change is actually a perturbation of the energy balance of the globe caused by changes of atmospheric concentrations of greenhouse gases and aerosols. Changes in atmospheric composition cause a small imbalance between the two ERB components at the top of the atmosphere. For example, increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases have produced an evident global temperature increase (IPCC, 2007) accompanied by the post-2000 TOA ERB imbalance of about 0.9 W/m^2 as estimated by Trenberth and Fasullo (2010). This planetary energy imbalance is too small to be measured directly from satellites considering the uncertainties in TOA radiative flux measurements from current satellite instruments. For example, uncertainty in shortwave TOA fluxes from current Clouds and the Earth's Radiant Energy System (CERES) measurement due to uncertainty in absolute calibration alone is in the range of 2-4 W/m^2 and the corresponding uncertainty in longwave TOA fluxes is even bigger (Dong et al., 2008; Clerbaux et al., 2009; Loeb et al., 2009a; Matthews, 2009). Nevertheless, sufficiently stable satellite measurements can be achieved with proper pre-launch sensor characterization, in-flight calibration, and post-launch validation so that it is possible to track relative changes in the net radiation by measuring incoming solar radiation and outgoing thermal infrared radiation for a long time period. In order to achieve a more complete understanding of changes of energy flows in the climate system due to anthropogenic climate forcing, the changes in cloud, water vapor, and surface properties also need to be monitored accurately and associated climate feedback processes need to be studied carefully. With the help of a long-term, global, uninterrupted time records of the stable measurements of ERB along with high quality, well-calibrated measurements of imagers and sounders, it would be possible to better understand/predict climate change due to increases in the concentration of greenhouses gases and aerosols.

Measurements of regional and global radiation budget date back to the late 1950s when the first generation of meteorological satellites were launched (such as Suomi's ERB measurements from Explore VII and TIROS), and they were further enabled with the launch in the late 1970s of Nimbus 6 and 7, which carried the first true broadband radiation scanning sensors. NASA's Earth Radiation Budget Experiment (ERBE) flown on ERBS (some flown on NOAA-9 and -10 satellites in the mid-1980s) and the European Scanner for Radiation Budget (ScaRaB) project provided the second generation of true broadband data and the first scanners with sufficient spatial resolution to separate clear-sky scenes and allow for inferring cloud radiative effect. The third-generation instruments, CERES (Clouds and the Earth's Radiant Energy System), were included on the NASA's TRMM (1997-) satellite, and Terra (1999-) and Aqua (2002-) satellites of the EOS mission. Calibration and data analysis accuracy have improved with each generation of ERB instruments and processing. The CERES instrument will fly on the NPP (2011) and JPSS-1 (2015) satellites to continue the ERB measurement. For the JPSS-2 (2019) mission, another round of improvement of the ERB instrument and data analysis is expected considering the advance of technology and science during the intervening 20 years. To meet this objective, the National Environmental Satellite, Data, and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA) hopes to reevaluate the ERB requirement for the period beyond the JPSS-1 mission. To support this effort, the National Climate Data Center (NCDC) of NOAA/NESDIS organized an international workshop entitled: Continuity of Earth Radiation Budget (CERB) Observations – Post-CERES Requirements. The expected outcome of the workshop was:

1) Identify the purpose and current uses of Earth radiation budget observations.
2) Document the current status of research and applications of Earth radiation budget.
3) Identify observing system requirements for the continuity of the Earth radiation budget climate data records (CDRs).

The workshop was held in Asheville, North Carolina on July 13 and 14. Over thirty scientists from NOAA, NASA, the European Space Agency, academia, and industry attended (Appendix A). Three working groups (WG) were formed: WG-1, the User Requirements Group; WG-2, the Instrument Requirements Group; and WG-3, the Data Processing Requirements Group. The meeting opened with a plenary session in the morning of the first day. The first day afternoon and the second day morning were devoted to working group discussions and to writing opinions and recommendations with regard to the three expected outcomes from the workshop. A very brief summary of the major results of the workshop follows.

USER REQUIREMENTS SUMMARY

Long-term, consistent, and continuous Earth radiation budget measurements, including related surface radiation budget (SRB) estimates, provide fundamental metrics on the integrated effects of the entire climate system. Therefore, ERB data are critical for monitoring, analyzing, and assessing the states of the Earth's climate system, for the time scales from weeks to decades. ERB values are also fundamental products of climate models so that ERB measurements provide observations that can facilitate model improvements and allow scientists to assess the confidence in long-term climate predictions. In particular, ERB measurements have played prominent roles in the improvement of the models used for IPCC assessments. As the data-record of ERB measurement lengthens, the critical role of ERB observations in future improvement of the assessment models will grow. The benefits of long-term, consistent, and continuous ERB observations further extend to the government and industry sector for decision-making in a wide range of applications (e.g., renewable energy) that involve investment and resource allocation.

To meet the user requirements, the following recommendations are provided by the user requirement working group:

1) Future ERB measurement should follow the suggestions from the two community workshops aimed at specifying instrument accuracy and stability requirements for a range of ERB and atmospheric variables (Ohring et al., 2004; Ohring et al., 2007). Atmospheric variables that impact radiation (such as temperature, water vapor, clouds, aerosols, etc.) should also be measured according to the requirements outlines in the same two reports.

2) A minimum instrument stability requirement for reflected solar radiation is 0.3 W/m^2 per decade (with 95% confidence) considered adequate to resolve changes over a decade to within current estimates of climate noise, and to be consistent with potential climate variability. Instrument accuracy is not required at the same level, and 1 W/m^2 (with 95% confidence) is adequate. In the longwave (LW), a minimum instrument stability requirement of 0.2 W/m^2 (with 95% confidence) is needed to resolve changes over a decade to within current estimates of climate noise, and the instrument accuracy requirement is at the same level as shortwave (i.e., 1 W/m^2). These instrument accuracy levels must be achieved equally under all-sky conditions as well as for individual scene types whose spectral content is concentrated at either end of the Earth's reflected solar and emitted thermal spectra (e.g., clear ocean, clear desert, deep convective clouds, etc.).

3) In order to ensure continuity with the existing CERES ERB record, follow-on missions (after CERES FM6 on JPSS-1) must ensure that any changes in instrumentation, orbit, spatial resolution, ancillary inputs, do not introduce an artificial “jump” in the record. Namely, every effort should be taken to ensure that instrument spatial resolution is similar to existing CERES instruments and that the orbit be close to that of CERES Aqua, NPP and JPSS-1. It is of utmost importance that successive missions overlap by at least one year.

INSTRUMENT REQUIREMENTS SUMMARY

The difficulty in detecting and documenting climate change due to anthropogenic forcing lies in the calibration stability requirements. Instrument calibration uncertainty is the dominant source at long time (e.g., decades) and large space (e.g., global) scales (Wielicki et al, 1995). The goal of the Instrument breakout group was to provide guidance as to the design and implementation of an observational strategy which 1) ensures continuity of the existing ERB CDR’s (i.e. backwards compatibility and no gaps in observations) while 2) addressing the needs of the user community as documented in the User Requirements break-out group. This guidance should enable the development of a sensor and overall calibration and validation plan that is capable of complete characterization (temporal, spatial, spectral, etc.) of observations with sufficient accuracy from independent paths of traceability. Inherent in this goal, is the concept that a rigorous Calibration and Validation program is integral to the entire lifecycle of an observational program (Datla et. al, 2009). At the same time, an independent data record of ERB obtained from other sources (e.g., radiation transfer calculations using measured atmospheric and surface variables of climate quality) should be used to ensure the calibration stability of satellite broadband ERB measurement.

Future ERB sensor should have separate measurement for SW, LW and total spectral to bring redundancy. Calibration improvements implemented in future ERB observational systems should be in line with the recommendations in the 2006 Achieving Satellite Instrument Calibration for Climate Change (ASIC3) report (Ohring et al., 2007) as well as the NIST publication ‘Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing, NISTIR 7637’ (Datla et al., 2009). Calibration of imager instrument flying with the broadband ERB instrument is just as important as the calibration of the ERB instrument since any calibration drift in the imager instrument can affect the downstream data processing, for example, the selection of ADMs and the quality of the cloud and aerosol forcing data. The following specific recommendations are also provided by the instrument working group:

1) Ensure continuity of observations. Develop an implementation plan that minimizes the risk of a gap in record.

2) Establish a dedicated sensor 'Calibration Science Team' early in the program. This team is also responsible for the "vicarious" checks of calibration to complement the on-board calibration.

3) Design onboard calibration system as principal source of information for detecting and correcting sensor calibration drifts.

4) Ensure onboard calibration system monitors performance across entire spectrum.

5) Design calibration subsystems to ensure calibration targets are viewed through the entire optical train.

6) Implement rigorous and robust ground characterization procedures.

7) Develop numerical first principle sensor model.

8) Develop rigorous contamination control plans.

9) Establish hardware archive to preserve key witness samples, optical components, calibration materials.

10) Calibration oriented or weighted programmatic implementation.

11) Develop a long-term strategic plan to sustain CDR's.

12) A separate workshop, focused on implementation approaches, should be held within one year after the workshop to further define the recommendations in this report.

DATA PROCESSING REQUIREMENTS SUMMARY

Errors in satellite broadband ERB data products come not only from instrument calibration uncertainty but also from the uncertainties associated with algorithm implementation and data processing procedures (e.g., radiance-to-flux conversion, diurnal corrections, etc.). The data processing working group described the data processing aspects of determining the Earth's radiation budget from broadband satellite measurements and discussed the potential improvement in the data processing for the time period after JPSS-1 compared to the current CERES ERB data processing. The group also addressed the importance of producing retrospectively consistent long-term ERB CDRs. Based on the discussions, the following major conclusions and recommendations for the ERB data processing system of the future were made:

1) To determine whether user requirements could be better met, errors introduced in the data processing system should be studied and minimized. Careful study and attention should be paid to the following processing steps and components: Spectral correction, angular distribution correction, and diurnal averaging.

2) Input and ancillary data and observations from improved satellite observations and model simulations in the next 10 years should be used in future ERB data processing, especially the new operational observations from the JPSS-2 satellite instruments. The reanalysis data and assimilated data used should include these new operational observations, especially the measurements from the new sounders. High quality and well-calibrated imager measurements (i.e., VIIRS) for scene identification, cloud and aerosol retrievals, and surface albedo map are required.

3) The future Geostationary Operational Environmental Satellite (GOES) observations (e.g., GOES-R) should be used to replace the current GOES observations for a better retrieval of cloud properties and improvement of diurnal averaging. Specifically, currently used 3-hr GOES observations should be increased to at least 60 minutes for GOES-R to better capture the diurnal variation of cloud and radiation fields. Multi-channels GOES-R cloud retrieval should replace the dual-channels (0.65 and 11 μm) GOES cloud retrieval currently used in the CERES data production. Other future geostationary satellite observations from domestic and foreign institutional partners of NOAA should also be used in the same criteria as the NOAA GOES observations to extend the spatial coverage.

4) More channels (such as 0.83, and 8.5 μm) should be used for a better retrieval of the cloud and surface properties from the polar-imager JPSS/VIIRS compared to channels 0.65, 1.6, 3.7, 11, and 12 μm used for the EOS/MODIS imager in the current CERES data processing. Aerosol absorbing properties (single-scattering albedo) from APS observations and vertical profiles from globally assimilated aerosol data should be added to the aerosol optical thickness and particles size for a better quantification of aerosol radiative forcing (direct and indirect).

5) To ensure backward compatibility with the CERES ERB data products, Terra and Aqua CERES ADMs should be used, respectively, in the JPSS-2 ERB data processing for the JPSS-2 ERB instrument on the morning and afternoon sun-synchronous polar orbiter. If new ADMs are developed, they need to be applied to the entire reprocessed data record. At the same time, there is a need for producing CERES-like ERB product through reprocessing by using retrospectively consistent algorithms and inputs in addition to the improved products and algorithms in the phase of JPSS-2. Applying

CERES ADMs to the ERBE measurement should also be considered as one of the reprocessing effort.

6) Both radiation transfer models (RTM) and parameterized inversion models (PIM) should be used to determine the ERB products for redundancy. Aside from the TOA and surface ERB products, products in the atmosphere (e.g., on 680, 440, and 100mb levels) are also needed to better estimate cloud-radiative feedback. Narrow band radiation observations with high calibration accuracy and spatial resolution are needed for inter-comparison and cross-validation with the broad-band radiation observations and for filling the potential gaps in the broad-band data.

7) Ground-based observations of surface radiation budget, cloud, and aerosol for various climate regimes are required for the validation and improvement of the satellite products. Steady streams of long-term observations from ground based reference networks (such as BSRN) are needed for satellite validation. Short-term intensive field campaigns should be used as a supplement to the long-term surface observations.

SUGGESTED FUTURE PLANS AT NOAA

In response to the above recommendations from this workshop, NOAA should consider awarding a conceptual design study of the Earth radiation budget instrument (ERBI) for the time period beyond JPSS-1 and form an international science team to guide planning, implementation, and construction of the ERBI and related operational production of ERB climate data records (CDRs). Other countries are also developing ERB satellite instruments. International collaboration on the development of future ERBI and ERB data production should be actively pursued.

1. WORKSHOP OBJECTIVE AND ORGANIZATION

1.1 OBJECTIVES

As part of the National Oceanic and Atmospheric Administration (NOAA)'s consideration of the continuation of Earth radiation budget (ERB) observations from space beyond the JPSS-1 phase, the National Climate Data Center (NCDC) of NOAA organized an international workshop: Continuity of Earth Radiation Budget (CERB) Observations: Post-CERES Requirements. The workshop had the following three general objectives:

1) REVIEW THE USER REQUIREMENTS FOR EARTH RADIATION BUDGET OBSERVATIONS: To ensure that the major operational ERB products are defined and scientific requirements are understood.

2) DETERMINE THE OBSERVATIONAL SPECIFICATIONS FOR THE ERB INSTRUMENT AND ITS DATA PROCESSING SYSTEM: Given the user requirements, what are the design options for meeting those requirements? If budgetary constraints and schedule limitations prevent us from satisfying all of the user requirements, how can we ensure that the most important requirements are met?

3) DETERMINE WHETHER THE CURRENT GENERATION OF INSTRUMENTS AND DATA PROCESSING SYSTEMS SATISFY THE OBSERVATIONAL SPECIFICATIONS: Can we use proven technology from CERES for the future ERB instrument after JPSS-1? Are any changes/modifications needed? If so, what are they?

1.2 WORKSHOP ORGANIZATION

The workshop was held from July 13 to 14, 2010, at the National Climate Data Center, Asheville, North Carolina. More than 30 scientists from US government agencies (including NOAA and NASA), the European Space Agency, academia, and industry attended, as listed in Appendix A. Those who are unable to attend but provide input through email are listed in Appendix B. The agenda of the workshop is given in Appendix C. Three breakout working groups (WG) were formed and each led by two chairs: User Requirements Group (WG-1); Instrument Requirements Group (WG-2); and Data Processing Requirements Group (WG-3). The first day morning was devoted to invited presentations. The first day afternoon and the second day morning were primarily spent in break out group discussions, interspersed with plenary session for coordination and review purpose.

Two weeks prior to the workshop, a questionnaire was distributed through the workshop website and email lists so that attendees can prepare their discussions before actually meeting and those who were unable to attend could also make a contribution to the workshop through email. The questionnaire is also used by the two chairs of each working group for reference during the break out discussions. The working groups were asked to document their discussions and recommendations and submit a group report. The working group reports constitute the major contents of Sections 2, 3, and 4, respectively, of this workshop report. Acknowledgement is delivered in Section 5. Section 6 lists the references. The summary of the workshop is provided in the Executive Summary, preceding Section 1. This report will be distributed through the workshop website for review by the broader user community before it is finalized. The oral presentations and the notes of working group discussions are also posted on the workshop website.

As a follow up, NOAA should consider awarding a conceptual design study of the Earth radiation budget instrument (ERBI) for the time period beyond JPSS-1 and form an international science team to guide planning, implementation, and construction of the ERBI and related operational production of ERB climate data records.

2. USER REQUIREMENTS (URE)

(Authors: URE Working Group Co-chaired by Drs. Paul Stackhouse and Jeff Privette)

2.1 INTRODUCTION

The exchange of radiant energy between the sun, earth, and space is fundamental to climate. The net Earth radiation budget is determined by solar radiation absorbed by Earth and thermal infrared radiation emitted back to space. The regional patterns of solar radiation absorbed by Earth and thermal infrared radiation emitted back to space drive the atmospheric and oceanic circulations and determine how much energy is available to drive the hydrological cycle and the exchange of sensible heat between the surface and atmosphere.

2.2 IMPORTANCE OF CONTINUOUS ERB MEASUREMENTS

The continuous satellite record of Earth radiation budget observations dating back to 1978 (Figure 2.1) illustrates the importance of monitoring decadal changes in TOA radiative fluxes. Tropical mean top-of-atmosphere (TOA) LW radiation increased by 0.7 W/m^2 between the second half of 1980s and the 1990s, and then remained at approximately the same level during much of the 2000s. Tropical shortwave (SW) and net radiation between the second half of 1980s and 1990s also changed by -2.1 and 1.4 W/m^2, respectively (Wong et al. 2006). The recent IPCC report (IPCC, 2007) identified clouds as the primary source of the variability in these TOA radiation records, and speculated that the changes in clouds and TOA radiation may reflect natural low-frequency/multi-decadal variability of the climate system. If true, this argues that in order to quantify and fully understand climate change, accurate, global ERB and cloud observations are needed for several decades in order to resolve the variability.

The IPCC (2007) report also noted that the largest uncertainty in model prediction of future climate is associated with cloud radiative feedback. A global cloud feedback could amplify or dampen global warming. ERB measurements provide a critical constraint on cloud feedback (Soden et al., 2008). Figure 2.2 shows IPCC AR4 model results of the change in global mean surface air temperature and cloud radiative effect (CRE) under the A1b emission scenario. If we assume, for the sake of illustration, that we take a "wait-and-see" approach to determining climate sensitivity (i.e., wait until the trend emerges), the model simulations in Figure 2.2 suggest that monitoring the future evolution of CRE gives an earlier indication of what climate sensitivity trajectory we are on than does monitoring of the global mean temperature. For example, by 2050 an observational record of CRE would eliminate ~50% of the models as being inconsistent with the observed record. In contrast, a stable temperature record of any precision would distinguish only the 2 lowest sensitivity models, while the other 11 models would be indistinguishable from one other. The temperature response prior to 2050 is similar in most models because the more sensitive climate models have a stronger ocean response delay. Also, even though some models show increases and decreases in CRE over time, this should not be confused as positive and negative cloud feedback: all models in IPCC AR4 (and likely all previous models as well) actually have positive cloud feedbacks.

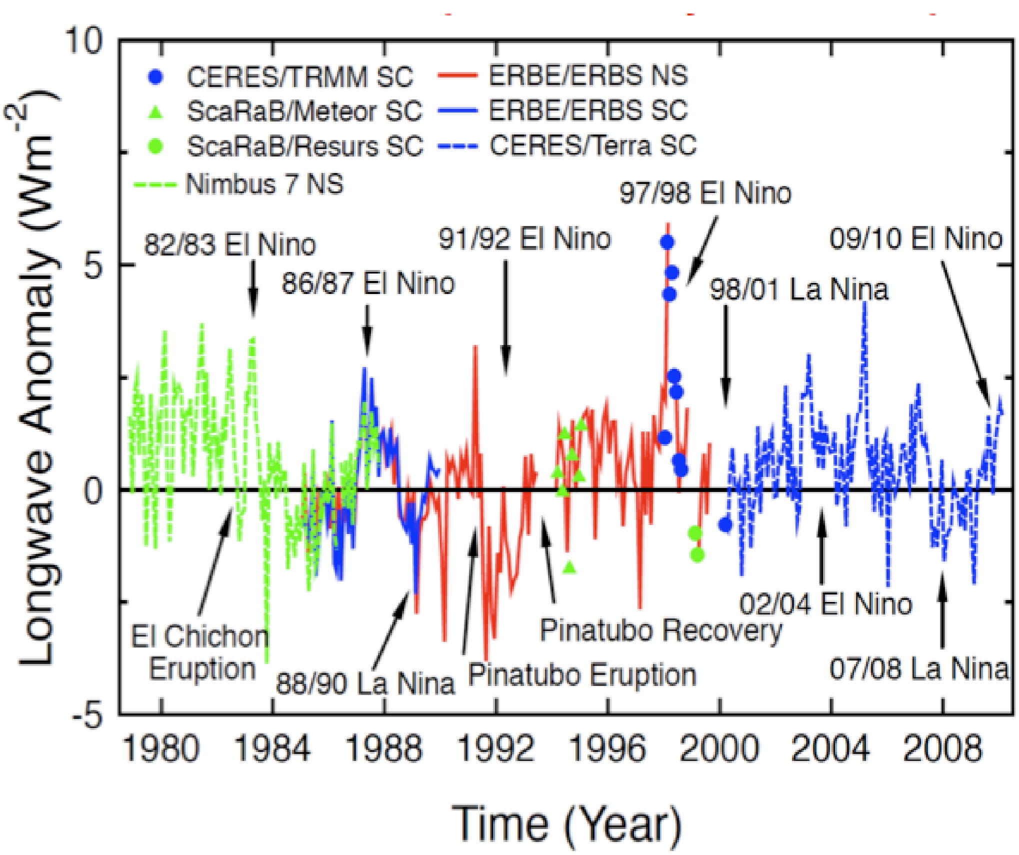

Figure 2.1. Time series of de-seasonalized tropical mean (20°N to 20°S) longwave anomaly (with respect to 1985–89 climatology) between 1979 and 2010 based on broadband scanner and non-scanner ERB instruments (Dr. Loeb, Workshop Invited Presentation).

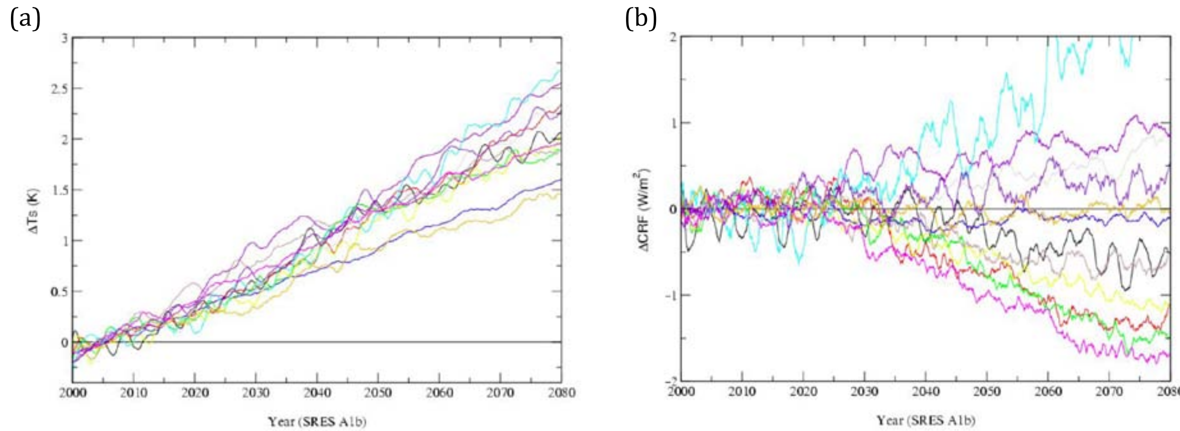

Figure 2.2. Change in global (a) surface air temperature and (b) cloud radiative effect between 2000 and 2080 for IPCC AR4 GCM simulations (5-year running means) (Soden et al., 2008).

The observational record to date and climate model simulations provide a compelling argument for continued observations of Earth's radiation budget and cloud properties. Recently, the Clouds and the Earth's Radiant Energy System (CERES) successfully reached a significant milestone: CERES generated its decade-long global climate data record of the Earth's Radiation Budget and associated cloud properties. The products may reach climate accuracy using broadband and imager instruments synergistically along with vigorous in-flight calibration effort (see Loeb et al., 2007; Matthews et al., 2005; Matthews, 2008; 2009). CERES instruments on the Terra spacecraft have been collecting science data continuously since March 2000, and CERES instruments on the Aqua spacecraft have been providing data since July 2002. The CERES record will continue with the launch of the CERES FM5 instrument on NPP in early 2012, and the last copy of CERES (FM6) will fly on JPSS-1 in 2015. Unfortunately, while the CERES instruments provide the radiometric stability needed to monitor changes in the Earth's TOA radiation, the absolute accuracy is insufficient to recover from a gap in the record. Loeb et al. (2009b) concluded that in essence, a gap restarts the climate record from zero, and the separate pieces of the record are forced to stand on their own. They noted that at least 1-year of overlapping measurements between successive instruments is needed, based on overlapping CERES Terra and Aqua data.

2.3 USER REQUIREMENTS

The difficulty in detecting and documenting climate change due to anthropogenic forcing lies in the calibration stability requirements. While algorithm implementation strategies (e.g., radiance-to-flux conversion, diurnal corrections, etc.) are the main sources of uncertainty at short time and space scales, instrument calibration uncertainty is likely the dominant source at longer time (e.g., decades) and larger space (e.g., global) scales (Wielicki et al, 1995). Following upon the extensive work by two community workshops aimed at specifying instrument accuracy and stability requirements for a range of ERB and atmospheric variables (Ohring et al., 2004; Ohring et al., 2007), a minimum stability requirement for reflected solar radiation is chosen as 0.3 W/m^2 per decade at 95% confidence level as being adequate to resolve changes over a decade to within current estimates of climate noise, and to be consistent with potential climate variability. Accuracy is not required at the same level, and 1 W/m^2 at 95% confidence level is adequate. In the LW, a minimum stability requirement of 0.2 W/m^2 at 95% confidence level is needed to resolve changes over a decade to within current estimates of climate noise, and the accuracy requirement is at the same level as shortwave (i.e., 1 W/m^2 at 95% confidence level). These accuracy levels must be achieved equally under all-sky conditions as well as for individual scenes types whose spectral content is concentrated at either end of the Earth's reflected solar and emitted thermal spectra (e.g., clear ocean, clear desert, deep convective clouds, etc.). Table 2.1 provides a summary of applications and requirements for ERB data products. Both threshold and objective (in parenthesis) values are listed. These requirements are needed for climate monitoring and climate and weather forecast model assessment. For example, daily and sub-daily data are useful to evaluate cloud and radiation parameterizations. Monthly data are useful to assess the statistical properties of the ERB simulated by the models. Trend information is extremely useful to evaluate climate feedbacks.

Table 2.1. Summary of Applications and Requirements for ERB Data Products. The requirements need to be met at 95% confidence level.

Application	Parameters[a]	Spatial Resolution[b] (km)	Temporal Resolution		Accuracy (W/m^2)	Precision (W/m^2)	Stability (W/m^2/decade)	
			Averaging Time	Sampling Time			SW	LW
Provide input data for climate monitoring and modeling	1): Solar irradiance	-	1 Month	daily	1.5 (0.8)[d]	0.3 (0.1)	0.3 (0.1)	-
	2-4): Global means	-	1 Month	3 (1) hours	1.0 (0.5)	2.0 (1.0)	0.3 (0.2)	0.2 (0.1)
	2-4): Zonal means	-	1 Month	3 (1) hours	2.0 (1.0)	4.0 (2.0)	0.5 (0.2)	0.3 (0.1)
	2-4): Regional means	250 (100)[c]	1 Month (plus daily variance) 1 day	3 (1) hours	5.0 (2.0) 10.0 (5.0)	10.0 (4.0) 20.0 (10.0)	0.5 (0.3)	0.5 (0.3)
	2-4): Mean diurnal cycle	250 (100)		3 (1) hours	5.0 (2.0)	20.0 (4.0)	-	-
	2-4): Synoptic scale	250 (100)	No averaging	At or interpolated to synoptic hours	10.0 (3.0)	20.0 (6.0)	-	-
	2-4): Surface fluxes	250 (100)	1 Month	3 (1) hours	10.0 (3.0)	20.0 (6.0)	0.3 (0.2)	0.3 (0.2)
Provide input data to and validation of output from NWP models	2-4): Regional means	250 (100)	No averaging	3 (1) hours	10.0 (3.0)	20.0 (6.0)	-	-

Notes on Table 2.1:

[a]Parameters are 1) solar irradiance, 2) outgoing LW radiation flux, 4) reflected SW radiation flux, 4) net radiation flux. For 2-4) this includes the clear-sky values as well as the total.

[b]This is the spatial resolution of the averaged product (i.e., the archive resolution), not the pixel resolution or instantaneous radiation flux (which may need to be much higher). For example, spatial resolution threshold for instantaneous radiation flux is 25 km and the objective is 10 km.

[c,d]The values are the threshold requirements and the values in the parenthesis are the objective requirements.

2.4 ADDITIONAL USER REQUIREMENTS

Continuous measurements of ERB and surface/atmospheric variables that are radiation active provide fundamental metrics on the integrated effects of the entire climate system. Because ERB values are also fundamental products of climate models, ERB measurements provide observations that can facilitate model improvements and allow scientists to assess the confidence in long-term climate predictions. In particular, ERB measurements have played prominent roles in the improvement of the models used for IPCC assessments. As the data-record of ERB measurement lengthens, the critical role of ERB observations in the improvement of future assessment models will grow. While other instruments provide information on changes in key climate variables such as aerosols and clouds, combing ERB measurements with the other instrument observations allows for the direct estimation of their radiative impact. For example, ERB observations collocated with observations from other sensors have led to improvements in our understanding of aerosol and cloud feedbacks and to a more quantitative estimation of these feedbacks on the global energy budget.

Long-term climate changes also manifest themselves in the short-term climate anomalies and weather extremes. Within the NOAA/NWS operational mission "… **for the protection of life and property and the enhancement of the national economy**…", ERB data are operationally used for monitoring, analyzing and assessing the states of the Earth systems, for the time scales from weeks to decades. For example, the NWS Climate Prediction Center routinely uses the near real-time OLR for detecting cyclones, assessing the weekly tropical hazard, and monitoring the evolution of sub-seasonal Madden-Julian Oscillation, and inter-annual El Nino. Also NWS Environmental Modeling Center used all components of ERB for validating and calibrating numerical forecast models. ERB provides the fundamental forcing information, and are essential for understanding the evolution of all dynamic systems.

In addition to the above climate monitoring applications, the benefits of long-term, consistent, and continuous ERB observations to the government and industry sectors include decision-making and modeling support. These are particularly useful for surface level radiative fluxes derived in ways consistent with the fluxes at TOA. Accurate estimates of the surface radiation budget (SRB) will support making decisions regarding the development of policy, adaptation and mitigation plans, and procedures for protection, response and recovery operations.

For example, the solar power industry requires estimates of the solar resource (i.e., solar energy incident to the surface of the Earth) useful for optimizing a wide range of solar technologies. Recent analysis of long-term satellite and surface based estimates of surface irradiance show changes ranging up to several W/ m^2 per decade for particular locations (i.e, Wild, 2009) while regional changes are complicated to evaluate due to paucity of surface sites relative to uncertainties in the current satellite records (Hinkelman et al., 2009), yet, there is consistency between satellite and surface patterns of variability (Pinker et al., 2005; Dutton et al., 2006). However, analysis shows decadal changes within seasons large enough to challenge the 10% solar industry standard (see Figure 2.3). Continuity of ERB reduces the uncertainty in estimating changes in the long-term resource and thus is important for the optimization of solar based systems. These sorts of technologies are becoming more important for larger scale use as a strategy for reducing carbon emissions through building and infrastructure heating, cooling and lighting.

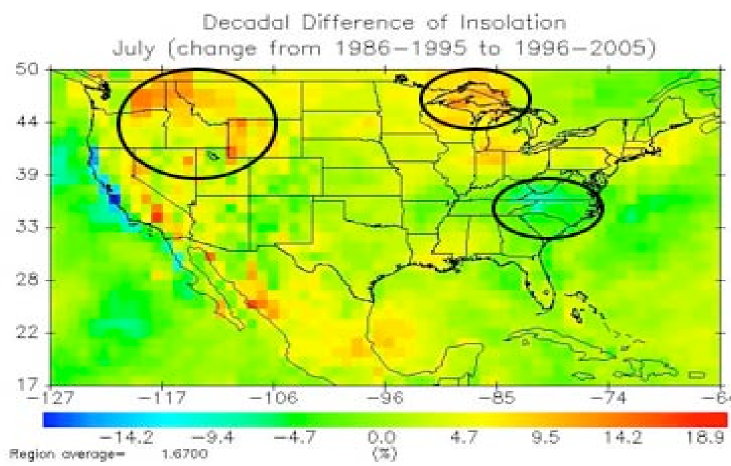

Figure 2.3. Percent changes of the solar irradiance for the month of July between the average of the periods 1986-1995 and 1996-2005. The circles show regions with peak changes greater than 10%, challenging industry standards for accuracy. The plot uses data derived from NASA's Surface meteorology and Solar Energy web portal (SSE). The irradiance values are adopted from the GEWEX Surface Radiation Budget Data set (Dr. Stackhouse, personal communication).

Besides the solar industry, a wide variety of areas require consistent and reliable solar information. These include the agricultural industry that relies upon consistent meteorological and solar resource from past and current growing seasons for in season crop modeling to estimate required watering, harvest times and yield projections. SRB fluxes are useful in a wide range of additional application from health threats, to water shed management, to energy efficient transportation.

2.5 SUMMARY AND RECOMMENDATION

Continuous Earth radiation budget measurements provide fundamental metrics on the integrated effects of the entire climate system. Because ERB values are also fundamental products of climate models, ERB measurements provide observations that can facilitate model improvements and allow scientists to assess the confidence in long-term climate predictions. In particular, ERB measurements have played prominent roles in the improvement of models used for IPCC assessments. As the data-record of ERB measurement lengthens, the critical role of ERB observations in the improvement of future assessment models will grow.

The benefits of long-term, consistent, and continuous ERB observations including related SRB estimates to the government and industry sector are important for national assessments, climate monitoring and are related to decision-making in a wide range of applications that involve investment and resource allocation. The specific requirements are summarized in Table 2.1.

In order to ensure continuity with the existing CERES ERB record, follow-on missions (after CERES FM6) must ensure that any changes in instrumentation, orbit, spatial resolution, ancillary inputs, do not introduce an artificial "jump" in the record. This means every effort should be taken to ensure that instrument spatial resolution is similar to existing CERES instruments and that the orbit be close to that for CERES Aqua, NPP and JPSS-1. Finally, as noted earlier, it is of utmost importance that successive missions overlap by at least one year.

3. INSTRUMENTS REQUIREMENTS (IRE)

(Authors: IRE Working Group Co-chaired by Drs. Kory Priestly and Istvan Laszlo)

3.1 INTRODUCTION

The Clouds and the Earth's Radiant Energy System (CERES) program produces a long-term record of radiation budget at the top-of-atmosphere (TOA), within the atmosphere, and at the surface with consistent cloud and aerosol properties at climate accuracy. CERES consists of an integrated sensor-algorithm-validation science team that provides development of higher-level products (Levels 1-3) and investigations. It involves a high level of data fusion, merging inputs from 25 unique input data sources to produce 18 CERES data products. Over 90% of the CERES data product volume involves two or more sensors. Broadband radiation is an 8-dimensional sampling problem that requires accurate handling of latitude, longitude, height, time, solar zenith, viewing azimuth, viewing zenith, and wavelength. In addition, long-term, consistent, and continuous ERB observations are also beneficial to the government and industry sectors in decision-making and modeling support.

At the heart of the CERES program are the CERES sensors. To date, five CERES sensors (PFM, FM1-FM4) have flown on three different spacecraft: TRMM, EOS-Terra and EOS-Aqua. CERES FM5 is scheduled for launch on the NPP spacecraft, and FM6 will fly on JPSS-1. The current effort pertains to requirements for the next generation of ERB instrument and observations which will commence with the JPSS-2 spacecraft. ERB CDR accuracy requirements begin with the sensor, the CDR cannot retain climate-level accuracy unless all potential biases from uneven Earth sampling in space, time, angle, and climate regime can be properly removed.

Over decadal time scales, the value of CDRs for both basic processes, science and applications increases if proper calibration and validation methods have been employed and documented and when associated uncertainties have been calculated and reported throughout the maturation process. With these concepts in mind, the international Global Climate Observing System (GCOS) has further defined a CDR as **"a long-term data record, involving a series of instruments, with potentially changing measurement approaches, but with overlaps and calibrations sufficient to allow the generation of homogenous climate monitoring"** (GCOS, 2006). Continuity and stewardship of CDRs apply to both science algorithms and radiometric traceability of the observations. The instrument group will only address radiometric traceability of the observations; it is assumed that the User Requirements breakout group will address long-term continuity and stewardship of the data products.

3.2 SENSOR OBSERVATIONAL REQUIREMENTS

Multi-agency sponsored workshops, known as Achieving Satellite Instrument Calibration for Climate Change (ASIC3), have been convened over the past decade to obtain and document input from the user community, with regard to observational requirements for CDR's. This instrument break-out group assumes that the requirements documented in section 7 of the 2007 ASIC report (Ohring, 2007), "Broadband Instruments" are the minimum requirements for future broadband ERB observations. These requirements, displayed in Table 3.1, are a factor of 2-5 more stringent with regards to radiometric accuracy and stability than the current CERES program. At the same time an independent data record of ERB obtained from other sources (e.g., radiation transfer calculations using measured atmospheric and surface variables in climate quality) should be used to ensure the calibration stability of satellite broadband ERB measurement.

Table 3.1. ERB Instrument Performance Requirements

Parameter	CERES Requirements	CERB Requirements
Wavelength Range	0.3 to 5 μm (SW) 5 to >50 μm, or 8 to 12 μm (LW) * 0.3 to >100 μm (TOT)	0.3 to 5 μm (SW) 5 to >50 μm (LW) 0.3 to >100 μm (TOT)
Radiometric Accuracy (End of Life. i.e. 5-yrs for CERES, 10-yrs for CERB)	1.0% (SW), k=1** 0.5% (LW), k=1 (5-year requirement) 0.5% (TOT), k=1	1.0% (SW), k=2** 0.5% (LW), k=2 (10-year requirement) 0.5% (TOT), k=2
Radiometric Stability	2%/decade, k=1 (Allocated from accuracy requirement)	0.3%/decade, k=2 (All wavelength ranges)
Radiometric Precision	<0.2 W/m2-sr + 0.1% of measured <0.45 W/m2-sr + 0.1% of measured <0.3 W/m2-sr + 0.1% of measured	<0.2 W/m2-sr + 0.1% of measured <0.45 W/m2-sr + 0.1% of measured <0.3 W/m2-sr + 0.1% of measured
Linearity	0.3% from linear over dynamic range, k=2	0.3% from linear over dynamic range, k=2
IFOV	~20 Km @ nadir (LEO)	~20 Km @ nadir (LEO)
Field of Regard	Limb to Limb	Limb to Limb
Operation	Continuous	Continuous
Design Life	5 years @ 0.85 probability	7 years @ 0.85 probability
Orbits (minimum of 1, 2	13:30 & 10:30 primary	13:30 primary, 10:30 secondary

simultaneous orbits preferred)***		

Note: * platform dependent, **k = sigma, *** minimize risk of a gap in the observational record.

3.3 CAPABILITY OF EXISTING CERES SENSOR DESIGN TO MEET CURRENT REQUIREMENTS

Sensor UV exposure and molecular contamination cause a loss of measurement sensitivity with time, particularly in the blue end of the solar spectrum (Matthews, 2009; Loeb, 2010). The degree of radiometric degradation, or spectral darkening, varies from mission to mission in an unpredictable manner, completely dependent upon the specific species of contaminant and operational scenario.

Figure 3.1 (left) compares normalized spectral radiances based on radiative transfer model calculations (MODTRAN) for typical Earth scenes (clear ocean and all-sky) with the CERES SW channel spectral response function overlayed. The Earth spectra contain a significant amount of energy at wavelengths < 0.5 μm, the region where spectral darkening is greatest. In contrast, the bulk of the energy for the CERES flight calibration lamps, Figure 3.1 (right), is concentrated at wavelengths > 1 μm, where spectral darkening is demonstrated to be minimal. Separately, the CERES solar diffusers, which would provide information about degradation below 0.5 μm, demonstrated instability in their reflectance of 1 to 7% depending upon sensor and mission.

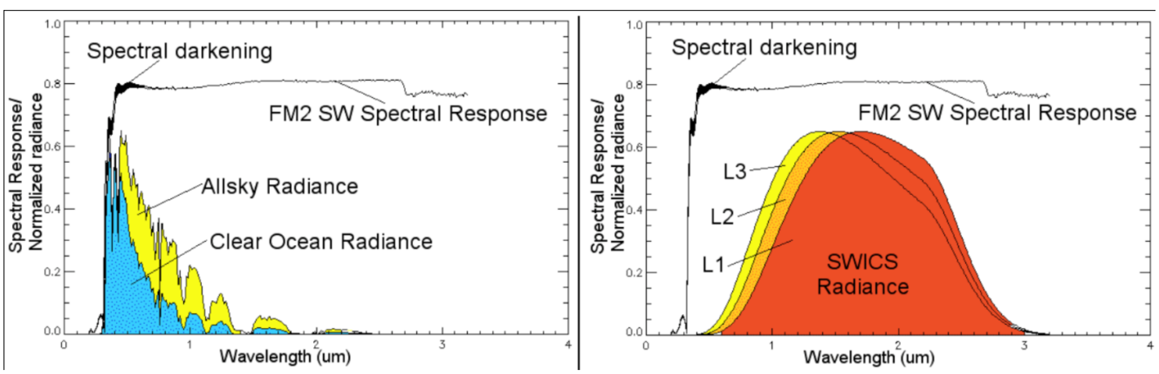

Figure 3.1. (left) Normalized spectral radiances for Earth scenes (clear ocean and all-sky) and CERES SW spectral response function; (right) normalized spectral radiances from CERES onboard lamps (levels 1-3) and CERES SW spectral response function (Loeb and Priestley, 2010).

Consequently, the CERES onboard calibration equipment failed to help detect, quantify, and correct for the spectral darkening observed on CERES FM1-FM4. CERES on Terra and Aqua were able to meet their performance requirements because multiple copies of CERES flew on each spacecraft and were operated in different modes (bi-axial and crosstrack), allowing separation of radiometric change as a function of operational mode. Future JPSS missions will fly only one CERES sensor per spacecraft and not benefit from these valuable intercomparisons. Thus, future ERB sensor should have separate measurement for SW, LW and total spectral to bring redundancy and facilitate the in-flight correction of the potential spectral degradation in the UV region. Since the problem of ensuring SW calibration in space for a broadband instrument has not yet been solved and it remains unclear what the best solution is, the requirement for onboard calibration to include coverage of the whole spectrum, improvement in onboard monitoring methods in conjunction with vicarious calibrations etc. are extremely welcome. For example, Matthews (2009) introduced a sophisticated contaminant mobilization and polymerization model that is constrained using observable calibration artifacts (and using deep convective cloud albedo for SE detector gain change). It is peer reviewed to show that the extent of CERES spectral darkening can be determined in a predictable manner and the CERES calibration can be improved accordingly.

Loss of traceability of the ERB radiometric scale, due either to a gap in the observational record, or insufficient overlap in preceding and succeeding missions would mean a break in the long-term ERB CDR. Loeb et al. (2009b) demonstrated that the ability of other flight sensors to span this 'gap' was inadequate, due to either insufficient stability requirements of other sensors, or inadequate sampling to fully transfer the characterization of the broad spectral and spatial coverage requirements. In the future, once CLARREO has demonstrated capability, it has the potential to carry the radiometric traceability across gaps in ERB observations. If there was a need to make a choice between a lower specification and data gap due to the limitation of schedule, risk, and cost, it is preferred to keep continuous data record by lowing somewhat specification.

3.4 CONCLUSIONS

The primary purpose of a sensor's onboard calibration subsystem is to enable calibration scientists to detect, quantify and correct for changes in a sensor's radiometric performance throughout the mission so that subtle changes in the climate system can be unambiguously detected. Lacking such information, the only viable option is to use intercomparisons with other sensors, or observations of Earth scenes to gauge the stability of the sensor. These approaches require considerable effort and depend upon the stability of the other sensors or scenes considered, which are generally not known at the required accuracy levels. Hence, reliable independent onboard calibration is vital (Ohring et al., 2005). Use of Earth scenes, lunar calibration, and intercomparisons with other flight sensors (e.g. MODIS, VIIRS, AIRS, CrIS, etc.) should also be used for validate and confirm the onboard calibration sources are performing as expected and demonstrating robustness in the broadband observational system. Calibration of imager instrument flying with the broadband ERB instrument is just as important as the calibration of the ERB instrument since any calibration drift in the imager instrument can affect the downstream data processing, for example, the selection of ADMs and the quality of the cloud and aerosol forcing data.

We strongly recommend that the upgrades and observations suggested in next section be adhered to and considered in the procurement of future ERB broadband sensors.

3.5 RECOMMENDATIONS

Future ERB sensor should have separate measurement for SW, LW and total spectral to bring redundancy and facilitate in-flight calibration effort. Calibration improvements implemented in future ERB observational systems should be in line with the recommendations in the 2006 Achieving Satellite Instrument Calibration for Climate Change (ASIC3) report (Ohring et al., 2007) as well as the NIST publication 'Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing, NISTIR 7637' (Datla et al., 2009). At the same time an independent data record of ERB obtained from other sources (e.g., lunar calibration or radiation transfer calculations using measured atmospheric and surface variables in climate quality) should be used to ensure the calibration stability of satellite broadband ERB measurement. With respect to onboard calibration of broadband sensors, the ASIC3 report recommended the following:

1) We recommend such partially redundant on-board calibrations to improve knowledge of instrument stability. Improvements are needed in broadband MAM or diffuser designs to meet the new climate stability requirements.
2) We recommend that future climate missions allow for regular deep space maneuvers to support climate calibration of zero radiance levels as well as lunar calibrations or characterizations of other radiometric components.
3) We recommend that more careful attention be paid to potential contamination of optical surfaces for climate instruments during ground testing, as well as improving the technologies for measuring and correcting any potential contamination.
4) We recommend that flight of the CERES FM-5 and -6 instrument use only the crosstrack scan mode to avoid in-orbit contamination of the SW channel optics. We also recommend that future calibration observatories in space be designed to explicitly account for expected in-orbit contamination, even if its level is small. The programmed scan mode should be an option as current CERES instrument but used only for necessary inter-calibration purpose.
5) Finally, future broadband instruments should examine the potential for 0.3 to 0.5 µm sources such as small nonlinear optics lasers to explicitly monitor throughput below 0.5 µm. This issue appears to exist for all instruments measuring solar radiation with wavelengths below 0.5 µm and should be accounted for in calibration system design.

In addition to the above general recommendations, more specific recommendations are also proposed below by the instrument requirement working group:

1. Ensure Continuity of observations

- Future ERB CDR should be backward compatible with existing record.
- Changes in instrumentation, orbit, spatial resolution, etc., should be carefully assessed as they can introduce a bias in the CDR that may not be easily corrected for during data processing.

2. Develop implementation plan that minimizes the risk of a gap in record (Loeb et al., 2009b)

- Supplement JPSS 1330 ERB observations with sensor on METOP 0930 orbit.
- Implement operational guidelines which ensure minimum of 12-month overlap in subsequent launches in JPSS and METOP orbits.

3. Establish a dedicated sensor 'Calibration Science Team' early in the program

- Members should include representatives from National Metrology Institutes, sensor vendor, and other radiation budget instrument teams.
- This team should meet early on and provide expert consultation during all aspects of the program.
- This team is also responsible for vicarious calibration using other sensors/earth targets.

4. Design onboard calibration system as principle source of information for detecting and correcting sensor calibration drifts

- On-board calibration subsystems should directly observe in-orbit contamination.
- Inter-comparison of vicarious targets with other sensors/earth targets serves only as independent validation.

5. Ensure onboard calibration system monitors performance across entire spectrum

- Incandescent lamps do not cover complete solar spectrum with sufficient energy.
- Combination of solar diffuser's, broadband lamps, and narrow band sources provides robustness.
- Specify accuracy requirements by scene types (e.g., all-sky, clear-sky ocean).
- Provide separate requirements for absolute accuracy and stability.

6. Design calibration subsystems to ensure cal targets are viewed through the entire optical train

- Applies to observations by both flight sensor and independent reference monitors.

7. Implement rigorous and robust Ground Characterization Procedures

- Continuously verify (re-verify) traceability of calibration targets as metrology improves

- Establish collaborations with National Metrology Institutes, such as NIST.
- It is highly important to measure the ground Transfer Active Cavity Radiometer (TACR) mirror's solar reflectivity, for example using the NIST SIRCUS facility.
- Implement rigorous configuration management procedures for all calibration data.

8. Develop numerical first principle sensor model

- Predict electrical, thermal and radiometric behavior of the final design.
- Verify performance utilizing characterization and calibration data.

9. Develop rigorous contamination control plans

- Protect optical surfaces during ground testing.
- Advance technologies for measuring and correcting potential contamination prior to launch.
- Design sensors such that the entire optical train is both inspectable and cleanable.

10. Establish hardware archive to preserve key witness samples, optical components, calibration materials

- Allows for subsequent testing to refine sensor uncertainty budgets as metrology improves.
- Allows for more rigorous analysis of flight anomalies.

11. Calibration oriented or weighted programmatic implementation

- Increase weighting/influence of Radiometric Performance in cost/schedule trades.
- Recognize that Ground Calibration is the last major test performed prior to shipment, when there are typically no financial or schedule reserves left.

12. Develop a long-term strategic plan to sustain CDR's.

- Calibration expertise (hardware, software, and staff) are needed not only before launch, but continually after launch to reach climate calibration accuracy and rigor.
- Recognize that post launch studies to investigate in-orbit calibration anomalies are difficult to fund, therefore efforts should be made to address this in defining long term programmatic structure and funding profiles.

13. Additional Workshop is needed.

- A separate workshop, focused on implementation approaches, should be held within one year after this workshop to further define the recommendations in this report.

4. DATA PROCESSING REQUIREMENTS (DPR)

(Authors: DPR Working Group Co-chaired by Drs. Xuepeng Zhao and Zhanqing Li)

4.1 INTRODUCTION

Earth radiation budget products include both solar-reflected/absorbed and Earth-emitted radiation from the top of the atmosphere (TOA) down to Earth's surface. Determination of Earth's radiation budget (ERB) components from satellite measurements requires intensive data processing as well as radiative transfer modeling efforts, especially for the determination of ERB in the atmosphere and on the surface. Accuracy of these quantities depends not only on the accuracy to which observing instruments have been calibrated, but to a large degree on the accuracies of input data and the inversion models used. It is therefore essential that we have the best possible models and input data in order to minimize the errors in the radiation budget data products (see Table 4.1a,b). Surface radiation budget (SRB) has been estimated from limited ground-based observations and global satellite measurements, but important discrepancies still exist even among the recent satellite-based estimates. These discrepancies are, however, much smaller than the systematic differences that used to exist between models and observation-based estimates (Li et al., 1997).

Table 4.1a. Comparison of historical estimates of the solar energy deposition estimated from ground and/or satellite observations (After Li et al., 1997, with updates).

Sources	Coverage	[a]TOA	[b]Surface	[c]Atmosphere
Abbot & Fowle (1908)	NH	0.37	0.42	0.21
Houghton (1954)	NH	0.34	0.47	0.19
London (1957)	NH	0.35	0.48	0.17
Sasamori et al. (1972)	SH	0.35	0.45	0.20
Budyko (1982)	Global	0.30	0.46	0.24
Rossow & Lacis (1990)	Global	0.31	0.49	0.20
Pinker & Laszlo (1992)	Global	0.29	0.50	0.21
Ohmura & Gilgen (1993)	Global	0.30	0.42	0.28
Li & Lighton (1993)	Global	0.30	0.46	0.24
Rossow & Zhang (1995)	Global	0.32	0.48	0.19
Kiehl & Trenberth (1997)	Global	0.31	0.49	0.20
Wild et al. (1998)	Global	0.30	0.45	0.25
Laszlo & Pinker (2002)	Global	0.30	0.48	0.22
Zhang et al. (2004)	Global	0.31	0.48	0.21

Loeb et al. (2009a), Kato et al. (2008)	Global	0.29	0.49	0.22
Trenberth et al. (2009)	Global	0.30	0.47	0.23
Wang & Pinker (2009)	Global	0.31	0.49	0.20
Stackhouse et al. (2010)	Global	0.30	0.49	0.22

Notes:

[a] is TOA reflected solar radiation and normalized by TOA incident solar irradiance, which is also called TOA albedo.

[b] is solar radiation absorbed by surface and normalized by TOA incident solar irradiance.

[c] is solar radiation absorbed by atmosphere and normalized by TOA incident solar irradiance.

Table 4.1b. Historical estimates of longwave fluxes lost to space, net atmospheric emitted longwave fluxes, and longwave fluxes emitted from the surface from ground and/or satellite observations. NH and SH stand for Northern and Southern Hemisphere, respectively.

Sources	Coverage	[a]TOA	[b]Surface	[c]Atmosphere
Houghton (1954)	NH	0.67	1.06	-0.23
London (1957)	NH	0.66	0.98	-0.24
Vonder Haar & Suomi (1971)	Global	0.69	—	—
Sasamori et al. (1972)	Global	0.67	0.97	-0.24
Smith et al. (1977)	Global	[d]0.73/0.71	—	—
		[e]0.72/0.70	—	—
Ellis et al. (1978)	Global	0.70	—	—
Wittman (1978)	Global	0.70	1.02	-0.24
Stephens et al. (1981)	Global	[f]0.68/0.69	—	—
Weare and Soong (1990)	Global	0.70	—	—
Rossow & Lacis (1990)	Global	0.66	1.16	-0.53
Rossow & Zhang (1995)	Global	0.69	1.15	-0.55
Kiehl & Trenberth (1997)	Global	0.69	1.14	-0.49
Wild et al. (1998)	Global	0.70	1.16	-0.55
Zhang et al. (2004)	Global	0.68	1.16	-0.53
Charlock et al. (2006)	Global	0.64	1.04	-0.44
Loeb et al. (2009a), Kato et al. (2008)	Global	0.70	1.17	-0.54
Trenberth et al. (2009)	Global	0.70	1.16	-0.52
Stackhouse et al. (2010)	Global	0.70	1.16	-0.54

Notes:

[a] is TOA outgoing LW radiation (OLR) normalized by TOA incident solar irradiance (341 W/m^2).

[b] is surface emitted LW radiation normalized by TOA incident solar irradiance.

[c] is net atmosphere emitted LW radiation normalized by TOA incident solar irradiance.

[d]Nimbus-3, July 1969/ERB, July 1975.
[e]Nimbus-3, August 1969/ERB, August 1975.
[f]Northern Hemisphere/Southern Hemisphere.

Section 4.2 will summarize the data processing procedures and models needed for the ERB data production. In section 4.3, the requirements on the input and ancillary data will be summarized. Following this, in section 4.4, there is a discussion of improvements needed to minimize the errors introduced in the data processing. Section 4.5 will provide some other recommendations for the data processing which are important for meeting future user requirements in climate monitoring and model simulations.

4.2 DATA PROCESSING AND MODELING

4.2.1 Production of TOA ERB data

Spectral correction, angular distribution correction, and diurnal averaging are the three major steps in the production of TOA ERB data. Errors introduced in these procedures should be minimized to produce climate quality TOA ERB products. The uncertainties introduced by these steps in current CERES data processing are summarized in Table 4.2.

Table 4.2. A summary of the uncertainties in the TOA fluxes introduced by the major data processing steps in current CERES data production (data are taken from Loeb et al., 2009a)

Error Sources	Global Monthly Mean (W/m^2)		
	Outgoing SW	**Outgoing LW**	**Net Incoming**
Spectral correction	±0.5	±0.25 (night); ±0.45 (day)	±1.0
Angular distribution correction	±0.2	±0.3	±0.4
Time and space sampling	±0.3	±0.3	±0.4
Inconsistent algorithms	negligible	negligible	negligible

The spectral correction model (SCM) is used to convert satellite measured filtered SW and LW radiances to their unfiltered counterparts. Then, the angular distribution model (ADM) is used to estimate the hemispheric flux from radiance observation made at a particular viewing geometry. An underlying assumption of ADMs is that the anisotropic factor is a characteristic of scene type, solar and viewing angles so that we can predict the integrated quantity, irradiance, given the scene type and the radiance at one view and solar zenith angle. Thus, ADMs needs to be constructed for a complete range of scene types describing cloud, aerosol, gaseous atmosphere and surface characteristics. From the instantaneous flux converted from the ADM model, a daily mean value is computed using a diurnal averaging model (DAM) to convert the specific time-of-day measurement to the daily average. To better capture the effect of fast changing scene types (such as cloud) on the estimation of a daily average radiation, current CERES data processing uses 3-hr GOES data to measure a relative diurnal cycle of radiation when computing the daily and monthly average irradiances (Young et al. 1998). It is necessary to have accurate SCM, ADM, and DAM for the production of TOA ERB data. TOA ERB can also be calculated using a radiative transfer model together with input datasets that quantify the properties of the atmosphere (gases, clouds, aerosols) and surface (Rossow and Zhang, 1995); this can be done as part of the determination of the in-atmosphere and surface ERB described below for physical consistency.

4.2.2 Production of ERB data at the surface and in the atmosphere

Solar energy reaching our planet is partly reflected back to space and partly absorbed in the atmosphere and the Earth's surface; the heated atmosphere and surface emit the energy back to space by thermal radiation. The deposition of solar energy and the emission of the Earth's thermal radiation are determined by the amount, vertical distribution, and optical properties of clouds, aerosol and radiatively active gases, as well as surface properties. Thus, ERB products are needed not only at TOA but also in the atmosphere and on the Earth's surface. In general, radiative transfer models (RTM) or parameterized inversion models (PIM) are used to estimates ERB at the surface and in the atmosphere. Some RTM approaches adjust the results to be consistent with TOA ERB measurements; the PIM approaches employ the TOA ERB measurements directly. Due to errors in radiative transfer calculations and in input variables, the ERB products in the atmosphere and on the surface are generally less accurate than the ERB at the TOA, but this not a necessary result. For example, modern estimates (since 1990s) of TOA albedo agree to within 1%, while surface absorption still differ by more than 2% on global scale (see Table 4.1a). On regional scales, the differences are even larger. Thus, accurate production of ERB data on the surface and in the atmosphere depends on the quality of the RTM (or PIM) as well as its input and ancillary data.

4.3 REQUIREMENTS ON INPUT AND ANCILLARY DATA

The quality of input and ancillary data and observations directly influence the accuracy of ERB products. It is worth to address high quality and well-calibrated measurement from imager (i.e., VIIRS) and sounder (i.e., CrIS) flying together with the ERB instrument are necessary for scene identification, cloud and aerosol retrievals, surface temperature, and generation of surface albedo and emissivity maps. Table 4.3 summarizes the input and ancillary data needed for ERB data production. Some of these data need to be updated and improved in the JPSS-2 phase compared to those used in the current Terra and Aqua CERES data production, which will be addressed in the next section.

Table 4.3. Input and ancillary data and observations needed for ERB data production. The potential sources of these data in the JPSS-2 phase are also given.

	TOA	Surface & In-Atmosphere
SW	Solar input (e.g., TSIS): solar constant Polar-Imager input (e.g., VIIRS): a) retrieved cloud properties (cover, optical thickness, phase, particle size, estimated layer thickness) b) retrieved aerosol properties (optical thickness, particle size, single-scatter albedo) c) surface albedo map Geo-Imager input (e.g., GOES-R): retrieved cloud properties (cover, optical thickness, phase, particle size) JPSS atmospheric sounder profiles (e.g., CrIS, ATMS/MIS) or reanalysis atmosphere profiles (e.g., NCEP reanalysis): T, W Others: a) snow/ice map (e.g., ATMS/MIS product) b) ozone profiles (e.g., OMPS)	Polar-Imager input (e.g., VIIRS): a) retrieved cloud properties (cover, optical thickness, phase, particle size) b) retrieved aerosol properties (optical thickness, particle size) c) retrieved aerosol single scattering albedo from surface and/or satellite d) surface albedo map Geo-Imager input (e.g., GOES-R): retrieved cloud properties (cover, optical thickness, phase, particle size) JPSS atmospheric sounder profiles (e.g., CrIS, ATMS/MIS) or reanalysis atmosphere profiles (e.g., NCEP reanalysis): T, W Others: a) snow/ice map (e.g., ATMS/MIS product) b) ozone profiles (e.g., OMPS) c) assimilated aerosol products (e.g., GOCART or MATCH) d) ground-based measurement for validation (e.g., ARM and BSRN)
LW	Polar-Imager input (e.g., VIIRS): retrieved cloud properties (cover, cloud top height and temperature), cloud vertical structure Geo-Imager input (e.g., GOES-R): retrieved cloud properties (cover, cloud top height and temperature, cloud vertical structure) JPSS atmospheric sounder profiles (e.g., CrIS,	Polar-Imager input (e.g., VIIRS): retrieved cloud properties (cover, cloud top height), estimated cloud base, cloud vertical structure Geo-Imager input (e.g., GOES-R): retrieved cloud properties (cover, cloud top height, estimated cloud base, cloud vertical structure) JPSS atmospheric sounder profiles (e.g., CrIS,

	ATMS/MIS) or reanalysis atmosphere profiles (e.g., NCEP reanalysis): T, W, Surface skin temperature Others: Spectral infrared surface emissivity map	ATMS/MIS) or reanalysis atmosphere profiles (e.g., NCEP reanalysis): T, W, Surface skin temperature Others: a) location of temperature inversions. b) ground-based measurement for validation (e.g., ARM and BSRN)

4.4 POTENTIAL IMPROVEMENTS

To improve the ERB products beyond JPSS-1 phase, the followings are suggested to take advantage of more and improved satellite observations available in the next 10 years:

1) Clear-sky aerosol ADMs should be developed to better quantify clear-sky TOA Earth radiation budget. The NASA/Langley CERES team is investigating this possibility and results can be used in the JPSS phase.
2) Aerosol absorbing properties (single-scattering albedo) from APS observations and vertical profiles from globally assimilated aerosol data should be added to the aerosol optical thickness and particles size for a better quantification of aerosol radiative forcing (direct and indirect).
3) More channels (such as 0.83, and 8.5 μm) should be used for a better retrieval of the cloud and surface properties from the polar-imager JPSS/VIIRS compared to the channels (0.65, 1.6, 3.7, 11, and 12 μm) used for the EOS/MODIS imager in the current CERES data production (Minnis et al., 2008, 2009).
4) The GOES-R observations should be used to replace the current GOES observation for a better retrieval of cloud properties and improvement of diurnal averaging. Specifically, currently used 3-hr GOES observations should be increased to at least 60 minutes from GOES-R observations to better capture the diurnal variation of cloud and radiation fields. Multi-channels GOES-R cloud retrieval should replace the dual-channels (0.65 and 11 μm) GOES cloud retrieval used in the current CERES data production.
5) Sounder products should be used directly as much as possible based on specified temporal (coincident for the polar imagers and at least 1-hourly for the GEO) and spatial requirements. Reanalysis atmospheric profiles are another resource considering higher temporal and global spatial coverage. The reanalysis used should include the new radiosondes and new remote sounders of JPSS. New ozone profile from JPSS/OMPS and snow/ice maps from JPSS/ATMS & MIS should be used to replace currently used corresponding data.

4.5 ADDITIONAL RECOMMENDATIONS

The above suggested improvements mainly deal with the potential amplification of the instrument errors by the data processing procedures. Aside from these improvements, the working group also recommended the followings in order to meet the user requirements:

1) Data processing should be designed to ensure consistency over the entire data record. Major changes in instrumentation, orbit, spatial resolution, requirement for overlap, etc., can introduce an artificial “jump” in the ERB CDRs that may not be so easily corrected for during data processing. Consistent algorithm and inputs should be used whenever possible and detailed error assessments should be performed for all changes occurring during the data record (e.g. changing from MODIS to VIIRS cloud products).
2) To ensure backward compatibility with the CERES ERB data products, Terra and Aqua CERES ADMs (Loeb et al., 2005) should be used for the JPSS-2 ERB data processing if JPSS-2 ERB instrument is on the sun-synchronous (afternoon or morning) polar orbiter. If new ADMs are developed, they need to apply to the all data record through reprocessing. At the same time, there is a need of producing CERES-like products through reprocessing by using retrospectively consistent algorithms and inputs in addition to the improved products and algorithms in the phase of JPSS-2. Applying CERES ADMs to the ERBE measurement should also be considered as one of the reprocessing effort.
3) Both RTM approach and PIM approach should be used to determine the ERB products for redundancy. Aside from the TOA and surface ERB products, products in the atmosphere (e.g., on 680, 440, and 100mb levels) are also needed to better estimate cloud-radiative feedback.
4) Narrow band radiation observations with high calibration accuracy and spatial resolution are needed for inter-comparison and cross-validation with the broad-band radiation observations and for filling the potential gaps in the broad-band data (e.g., Lee et al., 2002, 2007).
5) Ground-based observations of surface radiation budget, cloud, and aerosol for various climate regimes are required for the validation and improvement of the satellite products. Both long-term observations on ground-base networks (e.g., BRSN) and short-term intensive field campaigns are need.
6) A new end-to-end computer simulation system is only necessary to provide better analytic guidance for the development of future ERB observing system if it is fundamentally different from the current CERES instrument. Otherwise, current CERES data processing components can serve as this purpose with limited modification.

With the appropriate improvements of data processing procedures and investments in ground processing hardware and software, we can look forward to timely and high quality ERB measurements and operational production of ERB climate data records (CDRs). As indicated in the user requirements, such information is urgently needed for understanding and monitoring climate change and for improving climate and long range weather forecasting.

5. ACKNOWLEDGEMENTS

We would like to express our sincere appreciation for the valuable contributions made by all workshop attendees (see Appendix A) and those who were unable to attend but provide the input through email (see Appendix B). The invited speakers, Prof. Bill Rossow at City College of New York, Prof. Brian Soden at University of Miami, Dr. Norman Loeb at NASA/Langley, and Dr. Ellsworth Dutton at NOAA/ESRL, are greatly appreciated for their introductory presentation in the plenary session. Special thanks also go to the co-chairs of the three working groups (Dr. Paul Stackhouse at NASA/Langley and Dr. Jeff Privette at NOAA/NCDC for WG-1; Dr. Kory Priestly at NASA/Langley and Dr. Istvan Laszlo at NOAA/STAR for WG-2; Dr. Xuepeng (Tom) Zhao at NOAA/NCDC and Prof. Zhanqing Li at University of Maryland, College Park for WG-3) for their efforts of leading the group discussions and documenting their group report.

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7. ACRONYMS

ADM:	Angular Distribution Model
ARM:	Atmospheric Radiation Measurement
AIRS:	Atmospheric Infrared Sounder
APS:	Aerosol Polarimetry Sensor
ASIC3:	Achieving Satellite Instrument Calibration for Climate Change
ATMS:	The Advanced Technology Microwave Sounder
BSRN:	Baseline Surface Radiation Network
CDR:	Climate Data Record
CERB:	Continuity of Earth Radiation Budget
CERES:	Clouds and the Earth's Radiant Energy System
CLARREO:	Climate Absolute Radiance and Refractivity Observatory
CrIS:	Cross-track Infrared Sounder
CRF:	Cloud Radiative Forcing
DAM:	Diurnal Averaging Model
DPR:	Data Processing Requirements
EOS:	Earth Observing System
ERB:	Earth Radiation Budget
ERBE:	Earth Radiation Budget Experiment
ERBI:	Earth Radiation Budget Instrument
ERBS	Earth Radiation Budget Satellite
FM:	Flight Model
GCM:	General Circulation Model
GCOS:	Global Climate Observing System
GEO:	Geo-synchronous Earth Orbit
GEWEX:	Global Energy and Water Cycle Experiment
GOCART:	GOddard Chemistry Aerosol Radiation and Transport Model
GOES:	Geostationary Operational Environmental Satellite
GOES-R:	Geostationary Operational Environmental Satellite – R Series
GERB:	Geostationary Earth Radiation Budget
IPCC:	Intergovernmental Panel on Climate Change
IR:	Infrared
IRE:	Instrument Requirements
JPSS:	Joint Polar Satellite System
JPSS-1:	Joint Polar Satellite System – phase 1
JPSS-2:	Joint Polar Satellite System – phase 2
LEO:	Low Earth Orbit

LW:	Longwave
MAM:	Mirror Attenuator Mosaic
MATCH:	Model of Atmospheric Transport and Chemistry
METOP:	METeorological Operational Satellite
MIS:	Microwave Imager/Sounder
MODIS:	Moderate Resolution Imaging Spectroradiometer
MODTRAN:	MODerate resolution atmospheric TRANsmission
NASA:	National Aeronautics and Space Administration
NCDC:	National Climate Data Center
NCEP:	National Center for Environment Prediction
NESDIS:	National Environmental Satellite, Data, and Information Service
NIST:	National Institute of Standards and Technology
NOAA:	National Oceanic and Atmospheric Administration
NPP:	NPOESS Preparatory Project
NWS:	National Weather Service
OLR:	Outgoing Longwave Radiation
OMPS:	Ozone Mapping and Profiler Suite
PIM:	Parameterized Inversion Model
RTM:	Radiation Transfer Model
ScaRaB:	Scanner for Radiation Budget
SCM:	Spectral Correction Model
SEREC:	Sensor for Earth's Radiant Energy and Climate
SRB:	Surface Radiation Budget
SSE:	Surface meteorology and Solar Energy web portal
STAR:	Center of Satellite Application and Research
SW:	Shortwave
SWICS:	SW Internal Calibration Source
TOA:	Top of Atmosphere
TRMM:	Tropical Rainfall Measuring Mission
TSIS:	Total and Spectral Solar Irradiance Sensor
URE:	User Requirements
UV:	Ultraviolet
VIIRS:	Visible/Infrared Imager Radiometer Suite
WG:	Working Group

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APPENDIX C: Workshop Agenda

July 13

08:30 – 08:45 Registration

08:45 – 09:00 Welcome and Introduction

09:00 – 09:30 Bill Rossow (City College of New York): Historical review and future perspective of satellite ERB observations

09:30 – 10:00 Brian Soden (University of Miami): Climate change monitoring requirements – constraints on the water and energy budgets

10:00 – 10:30 Break

10:30 – 11:00 Norman Loeb (NASA Langley): Earth radiation budget accuracy and variability determined from CERES observations

11:00 – 11:30 Ellsworth Dutton (NOAA/ESRL): Status and plans for surface radiation observations

11:30 – 12:00 Discussion and Charge to Breakout Groups

12:00 – 13:30 Lunch – provided on site

13:30 – 15:30 Breakout Groups

15:30 – 16:00 Break

16:00 – 17:00 Plenary – Initial Summary and Discussion of Breakout Groups

17:00 – Finish for the Day

July 14

09:00 – 10:30 Breakout Groups continued

10:30 – 11:00 Break

11:00 – 11:30 Plenary – Final Reports from Breakout Groups

11:30 – 12:00 Close Out and Actions

12:00 – End of the Workshop

NESDIS 113 **Proceedings of the International GODAR Review Meeting: Abstracts. Sponsors: Intergovernmental Oceanographic Commission, U.S. National Oceanic and Atmospheric Administration, and the European Community, May 2003.**

NESDIS 114 **Satellite Rainfall Estimation Over South America: Evaluation of Two Major Events. Daniel A. Vila, Roderick A. Scofield, Robert J. Kuligowski, and J. Clay Davenport, May 2003.**

NESDIS 115 **Imager and Sounder Radiance and Product Validations for the GOES-12 Science Test. Donald W. Hillger, Timothy J. Schmit, and Jamie M. Daniels, September 2003.**

NESDIS 116 **Microwave Humidity Sounder Calibration Algorithm. Tsan Mo and Kenneth Jarva, October 2004.**

NESDIS 117 **Building Profile Plankton Databases for Climate and EcoSystem Research. Sydney Levitus, Satoshi Sato, Catherine Maillard, Nick Mikhailov, Pat Cadwell, Harry Dooley, June 2005.**

NESDIS 118 **Simultaneous Nadir Overpasses for NOAA-6 to NOAA-17 Satellites from 1980 and 2003 for the Intersatellite Calibration of Radiometers. Changyong Cao, Pubu Ciren, August 2005.**

NESDIS 119 **Calibration and Validation of NOAA 18 Instruments. Fuzhong Weng and Tsan Mo, December 2005.**

NESDIS 120 **The NOAA/NESDIS/ORA Windsat Calibration/Validation Collocation Database. Laurence Connor, February 2006.**

NESDIS 121 **Calibration of the Advanced Microwave Sounding Unit-A Radiometer for METOP-A. Tsan Mo, August 2006.**

NESDIS 122 **JCSDA Community Radiative Transfer Model (CRTM). Yong Han, Paul van Delst, Quanhua Liu, Fuzhong Weng, Banghua Yan, Russ Treadon, and John Derber, December 2005.**

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